Fires in Ducts

Fires in Ducts: A review of the early research which underpins modern tunnel fire safety engineering

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Notation

A	Tunnel cross-sectional area (m^2)
c_i	Local mass concentration of gas species i
$c_{i,avg}$	Average mass concentration of gas species i
$\bar{c_p}$	Average specific heat capacity of the gases (kJ/g)
E	Energy (kJ)
Fr	Froude number
g	Gravitational acceleration (m/s^2)
H	Height of duct (m)
H_{vap}	Latent heat of vaporisation (kJ/mol or kJ/kg)
k_1, k_2	Proportionality constants, Equn. 4 & 5 (-)
L	Length scale (-)
L_b	Length of the backlayer (m)
$\dot{m}_A$	Mass flow rate of ventilation air (kg/s)
$M_f{}'$	Mass of fuel per unit length (kg/m)
Q	Heat release rate (kW)
$\dot{Q}'$	Heat release rate per m width of tunnel (kW/m)
$\dot{Q}_L$	Rate of heat loss into the walls (kW)
Q*	Dimensionless heat release rate (-)
r	Stoichiometric ratio of fuel/air
R	Tunnel radius (m)
t	Time (s)
T	Temperature (K)
T_o	Ambient temperature (K)
T_{avg}	Average down stream temperature (K)
T_{sm}	Temperature of the smoke layer (K)
u	Ventilation velocity (m/s)
v_c	Critical velocity (m/s)
v*	Dimensionless velocity (-)
V	Flame spread rate (m/s)
V_{avg}	Average downstream ventilation velocity (m/s)
$Y_0^{(0)}$	Oxygen supply rate (mol)
ε	Emissivity (-)
ρ_0	Ambient density of air (kg/m^2)
ΔH_c	Heat of combustion of the fuel (kJ/mol or kJ/g)
ΔT_{cf}	Temperature difference due to stratification (K)
ΔT	Local gas temperature rise (K)
ΔT_{avg}	Average gas temperature rise (K)

Subscripts

F	Full scale
M	Model scale

Abstract

Much of the early research which now underpins tunnel fire safety design was carried out experimentally, using small scale ducts. This paper reviews such experiments, mostly carried out in the 1960s, 1970s, and 1980s, highlighting the assumptions and limitations of the early studies, which may have been forgotten as the equations developed have been applied in practice in the subsequent years. The review covers three primary topics; fire propagation under 'turbulent slug flow' conditions, stratification & flame spread, and backlayering & critical ventilation velocity.

1 Introduction

The problem of tunnel fires is one of the most complex and interesting areas of modern fire research. The demand on existing road and rail infrastructure has increased dramatically over the past few decades, forcing existing tunnels to take more traffic, leading to more congestion than ever. New tunnels, built to accommodate extra traffic and to reduce travel times, are now being made wider, longer and more complex than ever before. In order to engineer fire safety solutions for these tunnels, the interactions of vehicle fire loads, ventilation systems and tunnel geometry must be fully understood.

Tunnel fires have attracted an increasing amount of attention in recent years, following a series of catastrophic fires which occurred in European road and rail tunnels at the turn of the century [1], and more recent fire disasters in road tunnels in China [2,3], resulting in many fatalities. Additionally, the cost of tunnel construction can be exorbitant, meaning there is demand for tunnels to have inherent fire safety to minimise the investment risk. Despite this, sufficient interest in tunnel fire research is still somewhat lacking, resulting in some study areas, such as critical velocity, receiving extensive research [4], while significant gaps in understanding remain in others.

Several full-scale tunnel fire experiments have been carried out across the past five decades, including pool fire experiments carried out in Switzerland in 1965 [5], in the UK in 1970 [6], in Austria in 1975 [7], and in the USA in 1995 [8], as well as solid fuel and occasional vehicle fire experiments carried out in Japan in 1980 [9], Finland in 1985 [10], Norway in 1992 [11], Japan in 2001 [12], and The Netherlands in 2001 [13]. Recent full-scale tunnel fire experiments have tended to focus on simulated truck loads, such as the Runehamar tests in Norway in 2002 & 2013 [14,15], and metro carriages, such as the Metro project in Sweden in 2011 [16] and tests carried out in Canada in 2011 [17]. While each of these tests has contributed to knowledge, the enormous expense of full-scale tests is often hard to justify, especially as the contribution to knowledge of any individual test is often minimal. For this reason, much recent research in tunnel fire behaviour has been carried out using small scale 'tunnel apparatuses' in established test centres like RISE in Sweden (formerly SP) [18] and the State Key Laboratory of Fire Science (SKLFS) in China [19]. These recent small-scale experiments are carrying on the tradition established in the pioneering research carried out using ducts in the 1960s and 1970s, which is the main focus of this paper.

The issue of underground fire safety is not a new one and pre-dates most of the significant fire incidents in vehicle tunnels. Much of the early research began in the 1960s in response to a large number of fatal fires in mines [20]. This research consisted of both theoretical and experimental studies, often driven by mining associations, such as the Safety in Mines Research Establishment in the U.K. and the U.S. Bureau of Mines. Due to the obvious expense and safety issues associated with large-scale tunnel experiments, many of the studies were carried out using small-scale ducts. Assuming similarities in the fire dynamics between full scale and reduced scale, meant that the results from duct experiments could be applied to full size mines and this research yielded many valuable observations and theories. Research in this field lost momentum as the mining industry waned, until it was revived with the recent concern over transportation tunnel fire safety.

The behaviour of fires in tunnels can be directly related to this early research in mines and ducts; however, many of these early studies appear to have been overlooked in recent research [21,22]. One reason for this may be that researchers, understandably, prefer to compare their theories to large-scale experiments, due to the problems and complexities of scaling laws. However, in some cases, this may have led to the theories themselves being overlooked and not investigated further. Another explanation is that the similarities between the subjects and the full extent of this research have not been fully appreciated, which may have resulted in some research being repeated.

The aim of this literature review is to produce a comprehensive overview of the historic theoretical and experimental research which was carried out regarding duct fires. This is intended to act as a summary of the pioneering work that was carried out on this subject and it is hoped that it will be a useful reference for the current tunnel fire safety engineering community. Particular attention is focused on early studies that are not widely referenced in modern research; since these are likely to be less familiar to the audience they are therefore of greater interest. By examining the concepts discovered in these early studies, the roots of different modern branches of tunnel fire science can be uncovered. This paper is presented as an overall narrative of the development of this subject, from research on fires in ducts to the modern research in transportation tunnel fires.

This literature review has been broken down into three broad themes. Section 2 examines the study of flame propagation in ducts under “turbulent slug flow”. This is further divided into the fuel-rich and oxygen-rich mechanisms of flame propagation to compare the similarities and differences between these. The theoretical and mathematical models developed to describe these mechanisms are examined and compared to the results of early duct fire experiments. In Section 3, the effects of stratification on flame spread are examined. Models based on the concept of Froude number correlations are compared to examine the ability of the Froude number to predict the degree of downstream stratification and the composition of the gas species within the stratified layers. Section 4 provides a summary of the phenomena of backlayering and critical ventilation velocity. These topics, which have gone on to be widely researched with regard to tunnel fire safety, originated in the general study of duct fires. A short summary of the scaling theory, required to convert the results of small-scale experiments for application to full-scale tunnels, is provided in Section 5

The scope of this literature review has generally been limited to the study of fires in ducts, building corridors and model-scale tunnels; however, research on large-scale tunnels and mine shafts is also included where it provides a foundation for the understanding of the subject as a whole. Literature reviews on the subject of tunnel fire research have been covered in depth by several other authors elsewhere [4,23,24], and so it is not the purpose of this work to reproduce their findings.

2 Flame Spread with Turbulent Slug Flow

This section focuses on the mechanisms governing flame spread in a duct under “turbulent slug flow”, a condition first introduced by de Ris [25]. This condition is the assumption that the gases are fully mixed within the duct cross-section and therefore the effects of stratification can be neglected. It was first used in order to develop a solvable mathematical model to describe the mechanisms occurring in a duct fire, and was adopted by many of the other researchers of the time as it greatly reduced the complexity of the problem.

This assumption was shown to be sufficiently accurate for fires in small-scale tunnels and ducts [26], since their small height prevents significant stratification. However, in larger-scale ducts, stratification is much more likely to occur as the temperature variation of the gases within is greater. This condition is discussed in more detail in Sections 3 and 4. The equations and concepts derived for turbulent slug flow, presented below, have occasionally been applied to full scale tunnels, apparently without consideration that the assumptions might not apply. The extent to which turbulent slug concepts can be applied in real tunnel conditions has yet to be adequately explored.

2.1 Modes of Propagation

Much of the earliest research on duct fires focuses on flame propagation in continuously lined ducts [27]. Here, the term "fire propagation" is used to describe the continuous propagation of the burning region along the fuel (not to be confused with fire spread, where the burning region grows in size) either from an ignition source to the surrounding area, or fire movement from one object to another across a separation distance. These terms are used interchangeably in some studies [e.g. 26,28], which can cause a lack of clarity about which mechanism is being discussed.

This concept of fire propagation is particularly relevant to the mining industry, since mine shafts tend to be lined with timber throughout. As transportation tunnels are unlikely to be lined with a flammable material, the relevance of this research to current applications is, to some extent, limited. However, this early research describes in detail the mechanisms of heat transfer in confined spaces and the dependence of fire behaviour on the fire size and ventilation conditions, providing an invaluable insight into the processes occurring within the duct.

In order to understand the context of the research into flame propagation, the different flame propagation mechanisms must be understood. There are two types of flame propagation in ducts: oxygen-rich and fuel-rich. An oxygen-rich fire is similar to a fire in the open in that the propagation of the flame is limited by the availability of fuel to burn. Only small changes in the temperature and gas composition occur, which do not affect propagation. In this type of flame propagation, some unreacted air is able to bypass the burning zone, leading to a relatively high minimum oxygen concentration in the downstream gases of around 15% [25].

However, this fire could grow large enough to increase the temperature to a level where it significantly increases downstream heat transfer, therefore increasing fuel availability and flame propagation. Increased downstream fuel availability would then lead to increased fire growth, temperature, etc., resulting in thermal runaway [29]. If the fire grows large enough, it could reach a size where the flame propagation is dependent on the availability of oxygen in the burning zone. This results in a fuel-rich fire where the downstream minimum oxygen concentration tends towards 0%.

Roberts [28] presented a detailed paper on the conditions that could cause a fuel-rich fire. Three main mechanisms were identified:

- Ignition from a small source, which spontaneously grows into a fuel-rich fire. This is likely to depend on properties of the fuel, such as its volatility.
- Ignition from a large source, across a sufficiently large length of fuel surface to support a fuel-rich fire.
- Transition from an oxygen-rich to a fuel-rich fire caused by a reduction in ventilation supply.

2.2 Steady-State Flame Propagation

The first pioneering experiments on fires in ducts under forced ventilation were carried out in the late 1960s by Roberts *et al.* [27,29,30] which enabled the identification of the two flame propagation modes. While these early researchers openly acknowledged that oxygen-rich fires are more likely in full-scale mines and tunnels, their main focus tended to be on fuel-rich fire propagation for two reasons:

1. Fuel-rich fires are much more severe than oxygen-rich fires as (by definition) they consume virtually all of the available oxygen. This means they have both a greater heat release rate and fire propagation rate and will therefore be the most conservative fire-loading scenario.
2. Fuel-rich fires generally reach a steady-state burning phase in practice, providing a convenient way to compare theory with quantifiable experimental results.

2.2.1 *Idealised model*

The problem of a one-dimensional duct experiencing steady state flame propagation under turbulent slug flow is particularly suitable for modelling due to the exact route that must be taken by the gases within. Since fuel-rich fires are ventilation-dependant, in a duct of constant ventilation velocity, uniform cross section and uniform fuel loading, the fire propagation rate is expected to be constant. This enables the stages of a fuel-rich fire to be examined as if stationary. The first and perhaps the most significant idealised model to describe this scenario was described qualitatively by Roberts & Clough [29], based on a series of duct fire experiments, as shown in Figure 1. This model has also been described and refined by de Ris [25] and more recently has been adapted by Ingason [31,32] as a model of burning during 'catastrophic tunnel fires'.

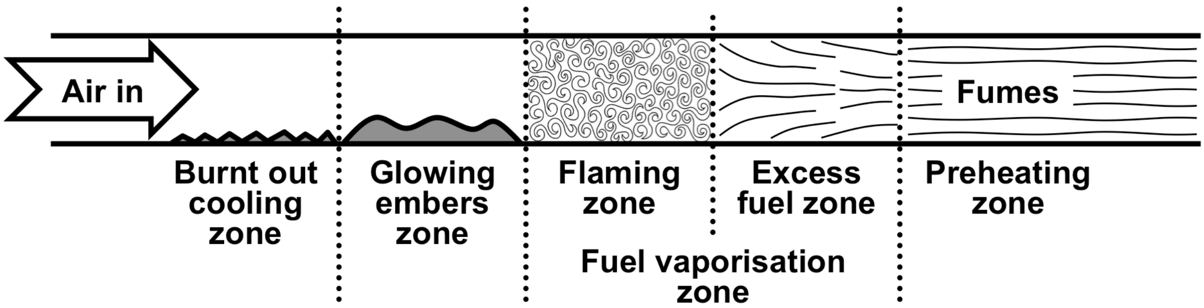

Figure 1 – Schematic of the idealised fuel-rich model of fire propagation. Adapted from [25,29].

As the air travels along the duct, it is first warmed by the duct walls in the "burnt out cooling zone" before encountering the "glowing embers zone". As smouldering combustion is still occurring in this region, the oxygen in the air is partially consumed and the air is heated further.

The air then reaches the "flaming zone" where flaming combustion occurs as soon as the concentration of fuel vapour in the air is high enough. This flaming combustion causes a large amount of heat to be released, which increases the temperature of the gaseous products and the solid fuel - therefore causing more fuel to be released. The oxygen from the incoming air is rapidly consumed and the oxygen concentration decreases to zero as the gas moves through the duct. The temperature of the gas reaches a maximum at the end of the flaming zone.

Past this point, there is no longer enough oxygen to consume all of the available fuel vapour and the gas reaches the "excess fuel zone". The gases travelling through this part of the duct are extremely hot and they continue to vaporize the fuel lining, which is unable to burn due to insufficient oxygen. When the temperature of the gas decreases enough to fall below the vaporisation temperature of the fuel, it enters the "preheating zone", where it continues to warm the fuel lining of the duct until the gas flow cools to ambient temperature.

2.2.2 *Mathematical models*

The earliest mathematical model of a steady-state duct fire was developed by Kennedy and Taylor [33] to evaluate the downstream temperature distribution based on the upstream gas temperature and the cross sectional geometry of the duct. However, this model was primarily concerned with the downstream temperature distribution and the conditions for ignition rather than the flame propagation velocity.

To create a complex mathematical model to describe flame propagation, de Ris [25] extended the idealised model outlined above and the corresponding mathematical relationships suggested by Roberts & Clough [29]. By assuming turbulent slug flow of the gases, de Ris developed a solvable mathematical model to describe the main heat and mass transfer processes occurring in the duct by applying a simple energy balance to each zone. Combining the energy balances from each zone produced an overall energy balance:

$$V = \frac{(\dot{m}_A Y_0^{(0)} \Delta H_c / r) - \dot{Q}_L}{M_f{}' H_{vap}} \quad (1)$$

where V is the fire propagation velocity, $\dot{m}_A$ is the mass flow rate of the ventilation air (mass/time), $Y_0^{(0)}$ is the oxygen supply rate, ΔH_c is the heat of combustion of the fuel, r is the mass of oxygen required to complete a stoichiometric reaction with a unit mass of fuel vapour, $\dot{Q}_L$ is the net rate of heat loss into the walls, $M_f{}'$ is the mass of fuel loading per unit length and H_{vap} is the net energy required to convert a unit mass of fuel from the solid to the gaseous state. In this equation, the quantity $(\dot{m}_A Y_0^{(0)} \Delta H_c / r)$ represents the heat release rate that is generated from a constant rate of oxygen supply from the longitudinal ventilation. Due to the assumption of thermally thick walls, heat losses from the duct occurred through conduction, resulting in radial temperature gradients in the walls.

Equn. 1 compared favourably with the experimental results of Roberts and Clough, showing that the fire propagation velocity is strongly dependent on the thermodynamic properties of the fuel used and the availability of oxygen to the fuel vapour in the downstream preheating zone. This paper proved to be significant in the research of duct fires and the mathematical model developed has formed the basis of many subsequent studies of both fuel and oxygen-rich flame propagation.

The boundary condition of thermally thick walls assumed by de Ris was appropriate for the specific application of mining tunnels and to examine the experiments carried out by Roberts and Clough. However, since convection from the duct walls is neglected, this model could not be applied to tunnels in which the walls were not semi-infinitely thick. Hunter & Favin [34] extended this study further to consider a thermally thin duct. Mathematical models of both an insulated duct and a duct that loses heat linearly were developed and it was found that, under certain conditions, the propagation of fire in a thermally thin duct behaved in a similar way to a thermally thick duct. This model is particularly relevant to the analysis of laboratory experiments, where it is often more convenient to create a model tunnel with relatively thin walls.

The behaviour of flame propagation along a fuel-lined duct is similar in many ways to horizontal flame spread over solid fuels. In the late 1970s, Fernandez-Pello [35] developed a mathematical model to describe steady-state flame spread over samples of PMMA in a small-scale wind tunnel. In this model, the flame spread rate was found to be a function of the ventilation velocity. Both thermally thick and thermally thin boundary conditions were considered. Although the problem was tackled in a similar manner to de Ris [25], by uncoupling the gas and solid phase reactions, no reference was made to this earlier mathematical model.

These early research papers focus almost entirely on the well-defined problem of a steady state, fuel-rich fire propagating in a duct under turbulent slug flow and, therefore, the results are extremely limited in their practical applications. In particular, the steady-state treatment of fire propagation considers only the effects of convection and radial conduction, but does not explicitly include the effects of radiation to the downstream fuel.

2.3 Transient Fire Spread

Transient fire propagation was not modelled until the late 1970s, despite experimental results that showed that this was by far the most likely type of fire in large-scale tunnels [36]. This is likely to be because of the complexities of the equations required for a complete mathematical model and the difficulties in solving all of them simultaneously.

For a given ventilation velocity, there is a critical minimum length, which governs whether or not the fire will propagate [37]. If the initial length of fuel that is ignited within the duct is very small, the heat transfer to the downstream fuel will be limited. This could mean that insufficient fuel vapours are released to enable the fire to propagate along the duct [28]. Since this fire cannot propagate, it will inevitably die out due to the limited depth of the fuel.

If the burning length is large enough to release sufficient downstream fuel vapour, the fire will propagate. Any increase in the burning length causes the temperature and therefore the propagation velocity also to increase. The amount of fuel vapour released increases rapidly as the temperature increases, causing more of the tunnel length to burn simultaneously. This acceleration continues until the burning becomes limited by the availability of oxygen to the fire and becomes fuel-rich.

A transient approach is required for the problem of creating a mathematical model for any type of fire spread that is time-dependent and therefore cannot be described as steady-state. When applied to the problem of duct fires, this includes:

1. Oxygen-rich fire propagation along a fuel – the rate of propagation depends on the availability of fuel vapour, therefore the effects of radiative preheating of the downstream fuel must be considered.
2. Fire spread from its point of origin to surrounding fuel within the duct.

An interesting feature of this research is that by considering the effects of radiation; the effects of other factors, such as the size and shape of the tunnel and the relative importance of radiative vs. convective heat transfer, can be investigated.

2.3.1 *Transient Flame Propagation*

In the late 1970s, following successful research by Bromberg & Quintiere [38] on radiative heat transfer in corridor fires, the U.S. Bureau of Mines began to investigate whether the same theory could be applied to fires in circular ducts. A two-dimensional mathematical model to describe this transient fire propagation in a circular duct was proposed by Edwards *et al.* [39]. In this model, the gas within the duct is assumed to be entirely transparent, meaning that radiative heat transfer only occurs with respect to the walls of the duct. The authors later amended this model to account for the effects of radiative heat transfer involving the absorbent gases [40]. This condition was considered to be more realistic for the scenario of wood burning in a mine fire due to the large amounts of black smoke that would be produced.

Since transient fire propagation is controlled by the amount of radiation from the hot gases downstream, rather than the availability of oxygen, the results of transient fire propagation could not be compared with the fuel-rich experimental fire data that had been collected by Roberts & Kennedy [27]. However, the mathematical model developed by Edwards *et al.* was found to compare favourably with results from the transition phase between oxygen-rich and fuel-rich wood duct fires, suggesting that in the former regime, radiative heat transfer was indeed dominant.

In a separate theoretical study into whether water spray suppression would be effective in preventing flame propagation in a fuel-lined duct, Habib [41] also investigated the effects of radiative heat transfer from gases of varying emissivity. While the results of this model agreed with Edwards *et al.* that radiation governs heat transfer to the fuel close to the flame front, the effects of radiation were found to decrease dramatically at larger distances, affecting the activation and design of downstream spray nozzles.

Research on this topic of continuous, transient flame propagation along a fuel-lined duct was not touched upon again until the 1990s. Rather than advancing on the two-dimensional models developed in the 1970s, Comitis *et al.* [42] extended the one-dimensional mathematical model developed by de Ris to account for transient fire propagation. Due to the assumption of a thermally thin duct, radiative heat transfer was considered in the outward direction only. Although similar issues to those of Edwards *et al.* were considered in this paper, this was not acknowledged by the authors - suggesting this earlier research may have been overlooked.

In a series of larger-scale testing carried out by the U.S. Bureau of Mines in the late 1980s, which studied fire propagation along conveyor belts in a model tunnel, Hwang & Litton [37] noted that the rate of flame spread reached a maximum at a ventilation velocity of 1.5 ms^{-1} and then decreased. For these tests, radiative heat transfer to the fuel appeared to govern flame spread - indicative that this was transient flame propagation. In these large-scale tests, the fire appeared to entrain oxygen from all directions (rather than just the direction of airflow), meaning that the flow of oxygen was three-dimensional. As a result, the two-dimensional models that had traditionally been assumed were invalid for these tests.

This discovery meant that new theoretical models were required to accurately model large-scale tunnel behaviour. However, the complexity of three-dimensional mathematical models meant that computer modelling studies [e.g. 43] were preferred for this research. As the results obtained in duct fire models were not always directly applicable to large-scale tunnels, these computational studies tended to be compared with the results of large-scale experiments, rather than duct fires.

As the focus of tunnel fire research gradually changed from mining fires to transportation tunnel fires, the issue of flame spread between objects, such as HGVs, became more relevant than fire propagation (involving lining materials). Additionally, the rapid increase of computer processing speed has made computer modelling of tunnel fire problems a much more practical option. As a result, computer modelling began to replace mathematical formulations and little research has been done on them since.

2.3.2 *Ignition Conditions*

All of the mathematical models discussed above have relied on the concept of a critical ignition temperature that governs the rate of fire propagation based on the temperature distribution downstream of the fire. In these models, the temperature distribution downstream has been calculated according to the various flame zones based on downstream heat transfer through a combination of radiation, convection and conduction.

In order to integrate the concept of radiative heat transfer into these flame spread models, Newman and Tewarson [26] developed a heat flow parameter to describe material ignition based on its critical ignition heat flux and dimensionless distance downstream. This theory was used in many future scaling theories and ignition models [44,45]. Ingason [44] found that an emissivity of $\varepsilon = 0.8$ gave a very good correlation with the results of his model scale tunnel fire tests.

3 Flame Spread with Stratification

Stratification can occur during a fire in a tunnel or duct due to the hot buoyant gases produced by the fire forming a hot gas layer along the ceiling, with a separate stream of cooler gases below, which is able to bypass the fire. Stratified flow is quite unlike turbulent slug flow and the transition between these two regimes has never been investigated. The effect of stratification was not considered in the earlier flame propagation models primarily to simplify the problem. In turbulent slug flow, the downstream conditions are simplified to a one-dimensional problem, with assumed uniformity of conditions across the full height and width of the duct at any given distance downstream. In turbulent slug flow it is assumed that the ignition conditions and fire propagation are controlled by the average gas temperature downstream. This assumption has been shown to be sufficiently accurate for duct fires [26], since their small height prevents significant stratification.

In larger-scale ducts (and tunnels), stratification is much more likely to occur as the temperature variation of the gases within is greater. This necessarily breaks the one-dimensional assumption of turbulent slug flow, considerably increasing the complexity of mathematically describing the system.

The effects of stratification in tunnel fires were considered in a few early research papers [46,47] however, these works tended to focus on the upstream phenomenon of backlayering (see Section 4.2), rather than its effect on downstream flame propagation. As will be seen, research has generally considered stratified upstream flow and stratified downstream flow as two distinct fields of study, with few studies considering both together until recently [48].

The Froude number was widely used in early research into backlayering and critical velocity, as will be discussed below, however, Newman [49] was the first to apply this theory to downstream gas flow. An experimental study of stratification in a large-scale duct was carried out to examine whether the Froude number could be used to predict the extent of downstream gas temperature stratification.

$$Fr = \frac{V_{avg}}{\left((\Delta T_{cf}/T_{avg})gH\right)^{1/2}} \quad (2)$$

where Fr is the Froude number, V_{avg} is the average downstream ventilation velocity, ΔT_{cf} is the temperature difference due to stratification , T_{avg} is the average downstream temperature, g is the gravitational acceleration and H is the height of the duct.

Newman found that this theory produced good agreement with experimental results [49], therefore verifying the relationship between the peak gas velocity and the Froude number, which had been proposed by Heskestad [50] for an unconfined flame. Overall, it was found that a Froude number less than 0.9 produced a gas flow in which the combustion gases were highly stratified and a Froude number of greater than 10 indicated that the gases were well mixed as in turbulent slug flow. The nature of the transitional flow conditions in a duct with a Froude number greater than 0.9 but less than 10 was not investigated and remains uncharacterised.

Comitis et al. [51] also carried out experiments on stratification in ducts to verify this correlation for highly stratified flow. In this study, the Froude number correlation was incorporated into a one-dimensional model that was able to successfully predict the fire-front behaviour and temperature profile of the fire plume.

Newman [49] also examined a second theory that had been proposed by Heskestad [52] – that the concentration distribution of an individual gas species within the duct varied according to the local gas stratification, and that these could be correlated through the average values. This theory can be expressed mathematically as:

$$\frac{c_i}{c_{i,avg}} = \frac{\Delta T}{\Delta T_{avg}} \quad (3)$$

where c_i is the local mass concentration of gas species i, $c_{i,avg}$ is the average mass concentration of gas species i over the cross-section of the duct, ΔT is the local gas temperature rise due to stratification and ΔT_{avg} is the average gas temperature rise within the duct cross section.

This theory correlated well with experimental duct fire results carried out by Newman [49], suggesting that the local gas concentration did vary according to the local gas temperature. Ingason [53] examined whether this theory could also be applied to the results of full-scale tunnel fire tests carried out in the Runehamar Tunnel. The results of these experiments indicated that this correlation also held well for large scale tests, only showing slightly more variation than the results of Newman.

This result is important due to the potential implications for full-scale and large scale laboratory testing. The instrumentation used for gas sampling and analysis in experiments is hugely expensive, while the cost of thermocouples is relatively cheap. This results in fewer gas sampling points in experiments than temperature measurements, often limited to just one or two. Using Equation 3 would enable the gas stratification to be extrapolated to multiple locations within the tunnel from limited local gas sampling results combined with the local and average temperature distribution.

Since the studies by Newman [49], research concerning the mathematical modelling of flame spread in stratified gases has gradually been replaced by computational modelling using programmes such as Fire Dynamics Simulator (FDS). Additionally, as the focus of tunnel fire research has gradually changed from mining fires to transportation tunnel fires, the issue of flame spread between objects, such as HGVs, became more relevant than fire propagation. Many computational studies have been carried out on this [e.g. 54,55,56] and compared with the results of large-scale experiments, leading to the general decline of research concerning small duct fires.

4 Backlayering and Critical Velocity

Backlayering, see Figure 2, occurs as a result of stratification, where the smoke layer formed at the ceiling may flow upstream against the ventilation flow, under certain conditions. The potential to control this flow of smoke (often the actual cause of death in fires) was of great interest to early tunnel fire scientists. If backlayering can be prevented, the smoke can be controlled so that one side of the tunnel is clear of smoke for egress and firefighting accessibility [57].

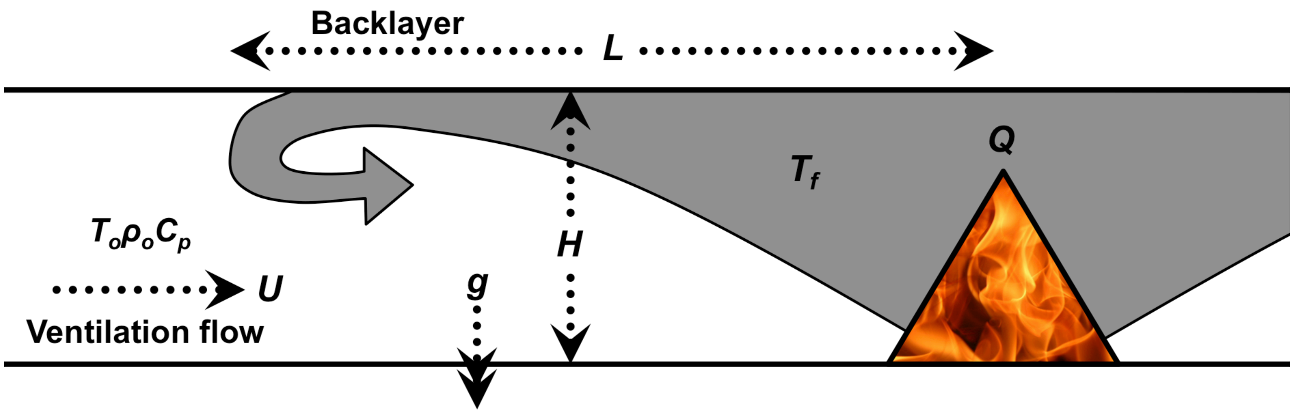

Figure 2 – Schematic of backlayering. Adapted from [58].

4.1 Critical Velocity

Thomas [59] was the first to investigate the conditions required to prevent backlayering. By relating the upstream velocity head to the buoyancy head caused by the hot gases, a semi-empirical correlation for the critical velocity required to prevent backlayering could be derived:

$$v_c = k_1\left(\frac{g\dot{Q}'}{T_{sm}\rho_0 c_p}\right)^{\frac{1}{3}} \qquad (4)$$

where v_c is the critical velocity (m/s), g is the acceleration due to gravity (m/s^2), $\dot{Q}'$ is the heat release rate per m width of tunnel (kW/m), T_{sm} is the temperature of the smoke layer (K), ρ_0 is the ambient density of air (kg/m^2) and c_p is the specific heat capacity of air (J/kgK). The constant of proportionality, k_1 was found to have the best agreement with duct fire experimental data when k_1=1.

This is the basic principle of the Froude number, where Fr=1 describes the point at which the critical velocity occurs due to the pressure heads of the upstream and downstream gases being equal. Compared with a full-scale duct, the critical velocity predicted by this correlation suggests that backlayering would be expected in mine fires [25,60], given their relatively low ventilation speeds [33].

In an investigation into corridor fire smoke behaviour, Hinkley [61] came up with a similar relationship based on the Froude number:

$$v_c = k_2 \left(\frac{g\dot{Q}' T_{sm}}{{T_0}^2 \rho_0 c_p}\right)^{\frac{1}{3}} \quad (5)$$

where T_0 is the temperature of the ambient air (K) and k_2 is a constant of proportionality.

By considering the interacting gas streams separately, Hinkley's approach results in a critical velocity that depends on both the temperature of the smoke, T and the temperature of the ventilation air, which is assumed to be ambient, T_0. The constant of proportionality, k_2 was found to have the best agreement with full-scale corridor experimental data when k_2=0.8. Heselden [62] evaluated the potential implications of Hinkley's results on tenability and firefighting in a hypothetical tunnel given different fire scenarios. Due to the clear practical relevance of these results, Helselden's work has had a significant impact on the treatment of critical velocity in tunnels [4].

The above models are based on a dimensional analysis, which only hold true when the flame height is less than the tunnel height. Oka and Atkinson [63] applied Froude scaling to Thomas' correlation to investigate this issue using results from model-scale tunnel tests. Although Thomas's correlation consistently overestimated the dimensionless critical velocity, v*, this analysis verified the cube root relationship with Q*. The dimensionless critical velocity was found to reach a maximum value at higher values of Q*.

Oka and Atkinson examined the relationship between the critical ventilation velocity and the dimensionless heat release rate and found that a maximum critical velocity existed, above which the backlayering of the smoke could be controlled for any dimensionless heat release rate. This maximum critical velocity is termed the "super critical ventilation velocity" and this concept was widely adopted within the fire safety community as a method of preventing backlayering in transportation tunnels for any size of design fire.

The dimensional analysis developed by Oka and Atkinson was used in many future studies on the conditions governing critical velocity in tunnels. A wide range of factors were considered, including tunnel slope [64], the use of hydraulic diameter as the characteristic length [65], tunnel aspect ratio [66] and the prediction of critical velocity using CFD analysis [67]. Details of these studies are not included here as they specifically relate to the subject of tunnel fires rather than duct fires; however, Ingason [4,32] presents a good summary of this research.

4.2 Backlayering Length

The work by Thomas [59] was the first theoretical research on tunnel fires, focusing on the movement of smoke in tunnel passages, particularly backlayering. Thomas proposed that backlayering occurs due to the buoyancy head caused by the hot gases being greater than the velocity head produced by the ventilation. This relationship, closely related to the Froude number, was then used to develop a correlation to predict how far this layer extends upstream:

$$\frac{L_b}{H} = 0.6\left(\frac{2gHQ}{T_{av}\rho_0 c_p u^3 A} - 5\right) \qquad \left(\text{for } \frac{1}{Fr} > 5\right) \quad (6)$$

where L_b length of the backlayer (see Figure 2) (m), H is the height of the tunnel (m) , Q is the heat release rate (kW), T_{av} is the average smoke temperature (K) , u is the ventilation velocity (m/s), and A is the tunnel cross-sectional area (m^2).

No further work was done by Thomas to investigate this correlation and consequently it was not compared with experimental data until a more recent study on model scale tunnel fires by Ingason [44]. Ingason found that by plotting a curve fit of Equn. (6) to backlayering results, it was possible to obtain a reasonably good correlation with model-scale test results. The critical velocity required to prevent backlayering in the model scale duct tests was calculated using Thomas' correlation and the curve fit, and the results were then scaled for comparison with large scale data. The corresponding full-scale velocities were calculated to be 5.2m/s and 3.4 – 4.17m/s respectively, which are slightly higher than the critical velocity for tunnels (usually quoted as 3m/s in literature [e.g. 25,37]).

In an investigation into the possibility of using the existing ventilation system in the Paris metro for smoke control, Vantelon et al. [68] proposed another correlation for the length of the backing layer:

$$\frac{L_b}{R} \propto \left(\frac{g\dot{Q}}{T_0\rho_0 c_p u^3 R}\right)^{0.3} \quad (7)$$

where R is the radius of the tunnel. Unlike Thomas' correlation, this relation is well known and is often quoted in studies on backlayering and critical velocity [57,63,69]. Equn. (7) was also compared to model scale tunnel fire results by Ingason [44] in a similar manner to Equn. (6); however, the correlation with test data was not as good. It should be noted that the experimental data used for this comparison was very limited, and more results would be needed to adequately validate these correlations.

4.3 Throttling

Throttling describes the tendency of a fire to resist the ventilation flow of the tunnel due to the additional volatile fuel gases and high temperatures that are generated by the fire [70]. This phenomenon, resulting from the interaction between the fire and the ventilation flow essentially caused a reduction the cross section of tunnel through which the ventilation flowed, resulting in this being reduced or "throttled".

This phenomenon was first investigated in the 1970s by Lee et al. [70]. In this study, it was discovered that the larger the fire, the greater the tendency of the fire to resist this ventilation. Throttling was largely forgotten by the fire science community after this study was published, which meant that the implications of this were not considered with respect to the "super critical ventilation velocity". The super critical ventilation velocity was first described by Oka and Atkinson [63] and it has since been used for the basis of many smoke management systems designed for tunnel fires.

This phenomenon was recently rediscovered by Colella et al. in modelling studies of tunnel ventilation in which the ventilation fans were explicitly modelled as well as the fire [71,72]. In subsequent research by Vaitkevicius et al. (2014) [21,22], throttling was examined using CFD modelling using FDS to demonstrate the effects of throttling on the critical ventilation velocity. It was found that although the critical ventilation velocity required to prevent backlayering does not increase above a certain fire size, the throttling effect of the fire on the ventilation meant that more fans were required to achieve this super critical ventilation velocity. This was a significant study, which showed that the throttling effect must be considered in fire safety design.

5 Scaling Theory

The study of fires in ducts was first introduced to examine the fire dynamics in laboratory-sized experiments that that could be extrapolated to full-scale tunnel and mine fires. In order to apply the results from small-scale tests to full-scale tunnels in a meaningful way, the effects of scaling must be understood. Scaling theory is used to translate small-scale tests into a corresponding large-scale system.

Scaling theory has been well researched with respect to fires in the open [73,74], and the same principles can be applied to tunnels. These scaling laws work by converting the values into dimensionless groups, depending on the geometric scale that is desired, and applying differential mass and energy conservation laws. The key scaling laws for parameters of interest in tunnel fires have been briefly outlined below. These have been adapted from the summary of scaling laws in Hansen and Ingason [75].

In these formulae, F is used to denote the full scale and M is used for the model scale. Therefore, $\frac{L_F}{L_M}$ represents the length ratio between the full scale and the model tunnel.

Heat Release Rate, $\dot{Q}$ (kW):

$$\dot{Q}_F = \dot{Q}_M \left(\frac{L_F}{L_M}\right)^{5/2} \qquad (8)$$

Velocity, u (m/s):

$$u_F = u_M \left(\frac{L_F}{L_M}\right)^{1/2} \qquad (9)$$

Time, t (s):

$$t_F = t_M \left(\frac{L_F}{L_M}\right)^{1/2} \qquad (10)$$

Energy, E (kJ):

$$E_F = E_M \left(\frac{L_F}{L_M}\right)^{3} \frac{\Delta H_{c,M}}{\Delta H_{c,F}} \qquad (11)$$

Mass, m (kg):

$$m_F = m_M \left(\frac{L_F}{L_M}\right)^{3} \qquad (12)$$

Temperature, T (K):

$$T_F = T_M \qquad (13)$$

Large-scale testing can be the most reliable method of determining quantities such as HRRs that will have a direct relevance to the values expected in real tunnel fires; however there are significant drawbacks in terms of the huge costs and safety considerations involved. When it is not possible or practical to carry out full-scale tunnel fire tests, model-scale experiments can provide a more convenient solution.

6 Conclusions

The overview of the historic research on the subject of fires in ducts shows that there has been a substantial number of experimental, theoretical and, more recently, computational studies carried out. The study of duct fires has spanned over fifty years and the results have been applied to a diverse range of practical applications, including fires in mine roadways, ventilation shafts, building corridors, and transportation tunnels.

Much of this research was devoted to the study of flame propagation in a fuel-lined duct to model the conditions of a fire in a timber-lined mine. The foundation of this research was the difference in the heat transfer dynamics observed in fuel-rich and oxygen-rich fires. Research on these mechanisms could be simplified by the assumption of turbulent slug flow, which meant that the downstream gases could be assumed to be fully mixed, and the problem could be simplified to one-dimensional.

The steady-state behaviour of fuel-rich fires made this an attractive starting place for the earliest studies, in which mathematical models were developed to describe flame propagation based on the heat and mass transfer downstream. An important finding of this research was the direct dependence of the flame propagation rate on the ventilation velocity. These models were developed to include thermally-thin boundary conditions as well as thermally thick, which enabled results to be compared to a wider range of experimental tests. Transient, oxygen-rich flame spread was also modelled with the radiative heat transfer to the downstream gases and it was found that this was the dominant heat transfer mechanism in this type of fire.

The effects of stratification on flame spread propagation was also examined and it was found that the Froude number could be used to predict the degree of stratification and the flame spread rate. An important finding of this early stratification research was that the local gas concentration and temperatures could be correlated through their averages. This has important implications for the evaluation of experimental tests in which the number of gas sampling points is limited.

The critical velocity has been extremely well researched, with a vast number of studies carried out in this area. A wide range of factors were considered, including tunnel slope, the use of hydraulic diameter as the characteristic length, the tunnel aspect ratio and the prediction of critical velocity using CFD analysis. The concept of critical velocity has been widely incorporated into the design of smoke control systems in fire. However, these designs do not account for the effect of throttling caused by the fire on the ventilation flow, which has recently been "rediscovered". The result of throttling means that more fans would be required to increase the effective ventilation velocity to the critical velocity as the heat release rate increases. This suggests that some ventilation systems could have been under-designed for the maximum design fire.

These early experimental and theoretical studies are limited in their applicability to modern transportation tunnels due to the vast difference between the type and orientation of fuel. However, their detailed analysis of the downstream fire dynamics provides a clear understanding of the heat transfer processes within duct fires, which has often been overlooked in more recent research.

While critical ventilation studies continue to this day, a number of fundamental questions remain unanswered, in particular regarding when equations derived from turbulent slug flow concepts can and should be used, and what happens in the transitional regime between turbulent slug flow and fully stratified flow. Future research investigating these questions, both at duct scale and at full scale, would be welcome.

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